Direct and Inverse Problems in Simulation of Human Ventricular Conduction System Electrograms

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Abstract **A 3-D model for the His Purkinje System (HPS) of the heart is used to solve the direct problem and simulate the HPS surface electrogram. The same model is also used to solve the inverse problem. Results from normal and pathological models are described.**

I. INTRODUCTION

Many heart defects occur not in the myocardium, but in the specialized conduction system of the heart, so called the His-Purkinje system (HPS). There exist various research studies into possible non-invasive measurement of the HPS signals [1-5], including a number of modeling studies [6-8]. Almost all these studies were based on a two dimensional models taking into consideration the left bundle branch only or were used to investigate the effect of HPS abnormalities on the surface ECG and not the HPS electrogram.

II. MODEL

The authors have previously reported a modified 3-D model for the HPS which avoids the defects of 2-D models [9]. It was based on the transformation of the two dimensional HPS sheet onto a three dimensional curvilinear system which resembles the ventricles in shape and dimensions. Computation of the surface potential was carried out using classical volume conductor theory [8]. To compare simulation results with those obtained experimentally, the standard orthogonal X, Y, Z leads were used. For each active element, φ_0 was defined using the dipole approximation:

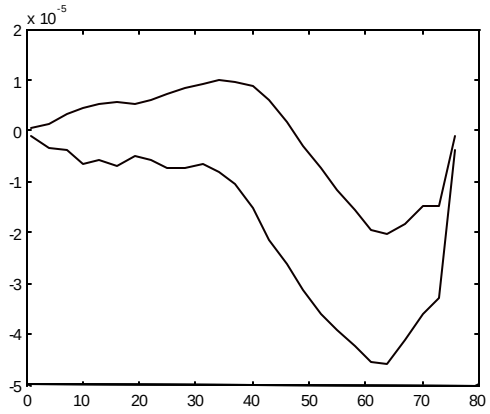
$$j_0 = \frac{1}{4ps}\oint_{r_o} j\nabla(l/r)dS = \frac{\dot{p}}{4ps}(1/r)_{r=r_0}$$

The equivalent current source **j** for each active element was assumed to be of the same magnitude, though different source strength can easily be introduced in the initial HPS matrix. A computer program explained in details in [9] was developed to simulate the propagation of excitation impulse throughout the HPS. The biopotentials originating from each active element were calculated individually and then summed to produce the total X, Y and Z HPS electrograms.

III. DIRECT PROBLEM

In the direct problem, we are trying to use our model for the simulation of biopotentials on the electrodes for further analysis by comparison with normal and pathologic cases. In the present paper we are trying to improve preliminary results [9] by changing the electrode positions for the best sensitivity to the potential variations caused by the defects in HPS. The standard algorithm explained in [9,10] was applied several times for different positions of the X, Y and Z electrodes. Every time the potentials were recorded as functions of time. Fig. 1. and Fig. 2. show in relative units the simulated potentials on the standard system of electrodes for the normal HPS. Fig. 1. shows the simulated signals obtained from the X electrode (upper curve) and Y electrode (lower curve). Fig. 2. shows the simulated signal obtained the form Z electrode. To study the effect of abnormality in the HPS, a complete Right Bundle Branch (RBB) block in conjunction with a partial Left Bundle Branc (LBB) block was simulated. This defect is known as left anterior hemiblock (LAH).

Fig. 1. X and Y simulated potentials from a normal HPS



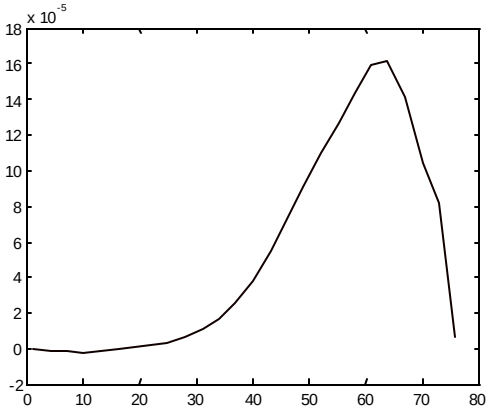


Fig. 2. Simulated Z potential from a normal HPS

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Abstract

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Fig. 3. shows the simulated LAH. Fig. 4. presents as an example the simulated signal obtained from the Z lead. For comparison, Fig. 5. shows the signal obtained from the electrodes placed in the intermediate position between X and Z electrodes.

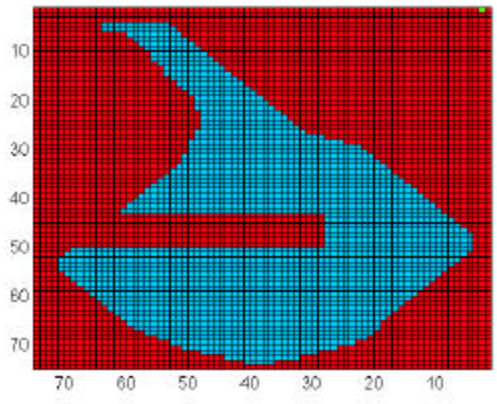


Fig. 3. Introduced LAH defect

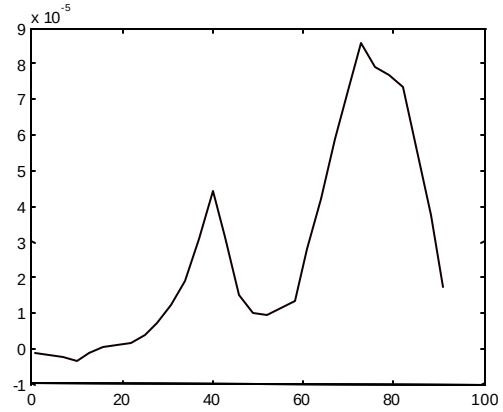


Figure (4): Simulated potential from the standard Z electrode for the case of LAH

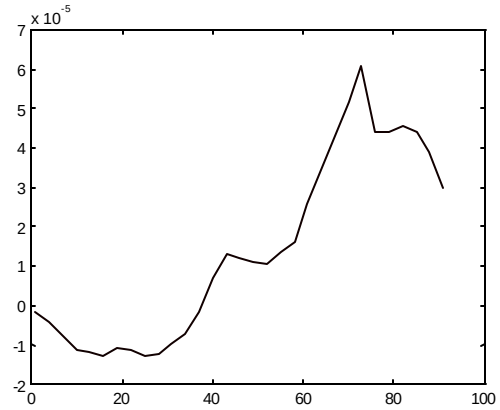


Figure (5): Potential from an intermediate (XZ) electrode for the case of LAH

Fig. 6. shows the signal obtained from the Z electrodes shifted 10 cm downward from the standard position. The electrode positions were changed several times to receive 12 independent signals used later for the solution of the inverse problem.

IV. INVERSE PROBLEM

Later [11], we presented an attempt to solve the inverse problem - that is to reconstruct the defect in HPS using the existing His Purkinje System Electrograms (HPSE). The main difficulty in this case is the insufficient amount of data to present the defect in details, so an approximate graphical solution was discussed in [11].

The inverse problem consists of the source modeling using the set of potentials at every electrode as a set of data. If we assume that the source is a single dipole, then we need only six independent electrodes to locate the source and define the vector of the equivalent dipole p. We solve numerically the system of equations:

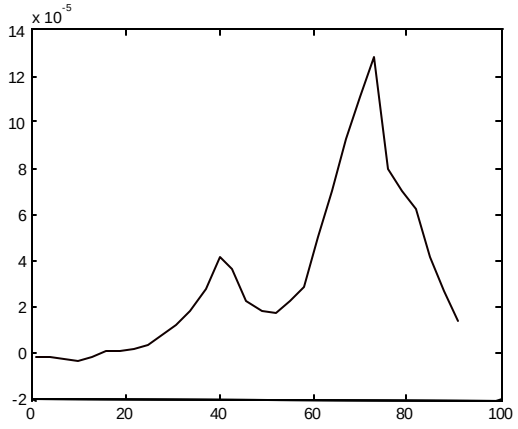
$$j_n = \frac{p\cos q_n}{s\,R_n^3} = \frac{p_x(x_n - x) + p_y(y_n - y) + p_z(z_n - z)}{s\,R_n^3}$$

where n is the number of the electrode (from 1 to 6),

$$R_n = \sqrt{(x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2}$$

x_n , y_n , z_n are the coordinates of the electrode, while x, y, z are the coordinates of the dipole. The solution gives three coordinates of the dipole x, y, z and three components of the dipole vector p_x , p_y , p_z .

The single dipole approximation is not complete for many cases, and the real system of sources consists of a moving string with a distributed set of dipoles. Exact calculation for this case requires multiple electrodes. Geometrical modeling gives an approximate graphical presentation of the defect in a single dipole approximation, but it can show the position of the defect without specifying its form. We described in [11] the attempt of a LAH defect reconstruction using insufficient experimental data.



Figure(6): Potential from the z -electrode, shifted 5 cm downward from the standard position

In the present paper we are trying to simulate the same defect and to receive maximum information varying the positions of the electrodes as described in the previous section to receive at least 2-dipole approximation. Figure (7) shows the 2- dipole reconstruction of the defect introduced in the previous section.

V. DISCUSSION

The HPS electrogram was simulated using a three-dimentional model of the LBB and the RBB. A program was developed earlier to simulate the propagation of excitation impulse throughout the HPS. The biopotentials originating from each active element were calculated individually and then summed to produce the total X, Y and Z HPS electrograms. A ramp signal that precedes the onset of the QRS complex of the ECG was present. When we introduced various LAH, the ramp was deformed in different ways. The detailed analysis of the figures similar to the examples shown in Figure (5) and Figure (6) helps to understand that the defect in the first half of the HPS (beginning from His bundle) is better recognized using intermediate electrodes placed between X and Z electrodes. The defects in the second part (Purkinje ramifications) require a shift of the electrodes along the Y axis and so on. The existing program is simple and can be used in any standard PC helping specialists to detect various types of the HPS defects.

The inverse problem is the most interesting one but it meets difficulties because of the insufficient information from standard 6-leads systems used in cardiographs. Changing the electrode positions according to the recommendations received from the direct problem we can increase the amount of information. Then the inverse problem can be solved with the developed method for multiple dipoles approximations to define the position and the form of the defect.

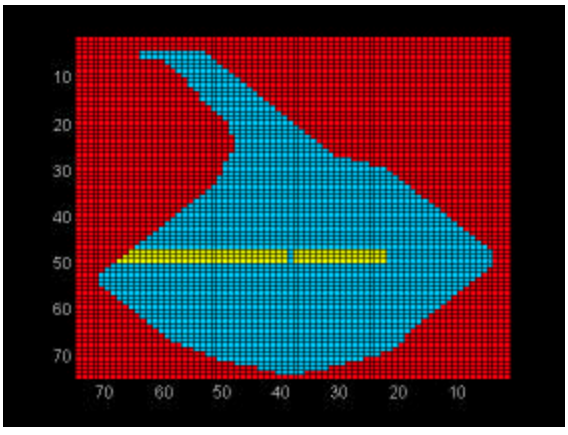


Figure (7): Reconstructed LA H defect

VI. CONCLUSIONS

The presented 3-D model of the heart conduction system is simple but together with the developed method of the simulation it can show the character of the signal propagating through the specialized conduction system of the heart. This information can be useful in the form of the direct problem resulting in the graphs showing biopotentials as functions of time. Those graphs can indicate the presence of the defects in the HPS. The same method can be used to solve the inverse problem beginning from experimental graphs and resulting in the defect reconstruction being especially effective in combination with the recommendation about the electrode positions taken from the direct problem.

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